

AMERICAN SOCIETY OF CIVIL ENGINEERS

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Hydrology of the Great Lakes

A SYMPOSIUM

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PAPERS

HYDROLOGY OF THE GREAT LAKES

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**A dissertation submitted in partial fulfillment of the requirements for the
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NOTE.—Written comments are invited for immediate publication; to insure publication, the last discussion should be submitted by **June 15, 1939.**

TYPICAL QUANTITATIVE ANALYSIS AS APPLIED TO LAKE SUPERIOR

BY C. R. PETTIS,¹ M. AM. SOC. C. E.

SYNOPSIS

A method of making a quantitative analysis of the hydrology of the Great Lakes, as illustrated by a detailed study of the hydrology of Lake Superior, is presented in this paper. Certain deductions are made, based on evidence from available data. By means of these deductions, values are obtained for the evaporation from the lake surface. Knowing the evaporation, the underground flow to the lake and the land losses can be computed.

The validity of the method has been checked by evaporation experiments which are described in the companion paper of this Symposium.

The conclusion reached is that the evaporation and the underground flow are greater, and the land losses are less, than the values that have been generally accepted.

INTRODUCTION

The hydrology of the Great Lakes has been the subject of several studies: Thomas Russell, of the United States Lake Survey (1906); the late John R. Freeman, Past-President and Hon. M. Am. Soc. C. E. (1926); Robert E. Horton, M. Am. Soc. C. E., and the late Carl E. Grunsky, Past-President, Am. Soc. C. E. (1927); and John F. Hayford and J. A. Folse (1930). Most of them assumed a value for evaporation determined from ordinary land pans; Mr. Freeman assumed that the underground flow to the lake was zero; all of their results differed considerably from those obtained by the present analysis.

A quantitative analysis of the hydrology of Lake Superior must account for the disposal of all the water that enters the main body of the lake, for such periods of time as may be considered. In any given period of time, the total quantity of water that enters the lake, as precipitation on the surface of the lake, river flow and underground flow, will be equal to the evaporation from the lake surface plus the flow through St. Marys River, plus the change in storage, as indicated by lake levels in the same period of time. If the river flow to the lake is known, and the underground flow to the lake can be determined, the tributary land drainage basin can be included in the analysis by using the relationship: Over a period of several years, the rainfall on the land basin is equal to the river flow to the lake, plus the underground flow to the lake, plus the land losses. The term "land losses" includes all land precipitation that does not reach the lake; presumably the land losses consist primarily of land evaporation and transpiration, or other vegetative losses.

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ANALYSIS

Formulas.—The following formulas apply to any given period of time:

$$P + R + U = O + S + E \dots \dots \dots (1)$$

and

$$B = R + U + L \dots \dots \dots (2)$$

All of the terms in the equations represent volumes of water in the period of time under consideration. They are defined as follows:

P = the rainfall on the surface of the lake, and becomes an immediate addition to the body of water in the lake as soon as it falls. It is assumed that the depth in inches of rainfall on the lake is the same as the depth of rainfall on the land; it was decided that this assumption would give better results in this analysis, because the evidence of a slight difference between P and B is conflicting.

B = the rainfall on the tributary land area. This value was computed from records of 59 stations of the United States Weather Bureau in the area, by taking a weighted average for the sections into which the area was divided.

R = the run-off into the lake from the surface streams as determined from stream-flow records of the United States Geological Survey and other sources, using a method of weighted averages, based on a personal reconnaissance of the area, 49% of which is covered by stream-flow records. The value of R , as a whole, is considered fairly accurate.

U = the net underground flow into the lake, which is not known, and is to be determined.

O = the outflow from the St. Marys River, which is based on careful records kept by the U. S. Engineer Department.

S = the change in storage in the lake, as indicated by gage records, being plus for a rising lake and minus for a falling lake. The gage records are kept by the United States Lake Survey.

E = the net evaporation from the surface of the lake, and is considered in the usual sense of evaporation minus condensation.

L = the difference between the rainfall B and the surface and underground flow into the lake ($R + U$), for the period under consideration, as given by a transposition of Equation (2).

The period of time used in most of this analysis is one calendar month. Symbols P , R , U , O , S , and E all denote quantities of water that enter or leave the main body of the lake during the month in question. Symbol B is the precipitation on the land area for the same month. In winter much of the precipitation remains on the surface of the ground and does not enter the lake, either as surface flow or underground flow, until the spring thaw. Throughout the year, the land precipitation, B , is subject to a delay before entering the lake, due to both surface and underground storage effects. For this reason, the value of L for any particular month, as obtained by Equation (2), will not represent the land losses (evaporation and transpiration) which pertain to the precipitation of that particular month, the land losses being that portion of the precipitation that does not ultimately enter the lake. Over a number of years,

the values of L for the period will represent the land rainfall that does not reach the lake; that is, the land losses, primarily land evaporation and transpiration.

There are two equations and three unknowns, E , U , and L . A rigid solution is impossible; but by making certain assumptions in accord with the present knowledge of the subject (and which, in most cases, seem to be the only reasonable assumptions possible, in view of the evidence) it is possible to arrive at an approximate solution. If one unknown is determined approximately, a rigid solution is possible for the other two unknowns, although the results necessarily cannot be more accurate than the approximate determination of the first unknown.

As far as is known, none of the lakes freezes over entirely in the winter. "Open-water" evaporation refers to the rate of evaporation from the part of the lake that is not covered by ice. The actual evaporation from a lake in the winter will be less than the "open-water" evaporation by an amount that depends on the extent of ice that is formed.

Since January, 1937, evaporation stations have been maintained by the Lake Survey at Detroit, Mich., Kewaunee, Wis., Duluth, Minn., and Buffalo, N. Y. An effort is made to keep the water temperature the same as the temperature of the water in the open lake, which makes them different from ordinary land-pan experiments.

Results reported by Mr. Hickman in this Symposium are based fundamentally on the evaporation experiments. In this paper, a mathematical analysis is made of data which is entirely different from that used by Mr. Hickman, and monthly values of the evaporation on Lake Superior are obtained. The results of the two independent solutions check rather closely; the results obtained by investigators who neglected underground flow do not check with the evaporation experiments. When the evaporation has been determined, by any method, the values of U and L can be determined mathematically from Equations (1) and (2). The analysis and solution given in this paper were made before the evaporation experiments were begun. It is evident from Fig. 1 that the remainder of this paper, with slight modifications, might be considered to be a solution and discussion based on the evaporation experiments.

From the data and Equations (1) and (2), monthly values of $(E - U)$, $(E + L)$, and $(U + L)$ can be obtained which will be as accurate as the data upon which they are based.

As a matter of convenience, in all computations, the water that will cover the land area tributary to Lake Superior to a depth of 1 in., will be used as a unit of volume. Unless otherwise indicated, all data will be given in the same unit. The land area of Lake Superior is 49 078 sq miles. One unit, or 1.0 in. of water on this area, will represent a certain definite quantity, which is practically 114 billion cu ft. The water area of Lake Superior is 31 817 sq miles. The ratio of land area to water area is 1.54. If a 1-in. depth of water on the land were placed in the lake, the lake level would be raised 1.54 in. Inches of depth on the land can be converted to inches of depth on the lake by multiplying by 1.54; and, conversely, inches of depth on the lake can be converted to inches of depth on the land by dividing by 1.54.

In this analysis, the following assumptions are made:

(a) It is assumed that the net underground flow into the lake, U , is always positive; that is, there will be no monthly period in which there is a net flow of underground water away from the lake. This assumption is definitely indi-

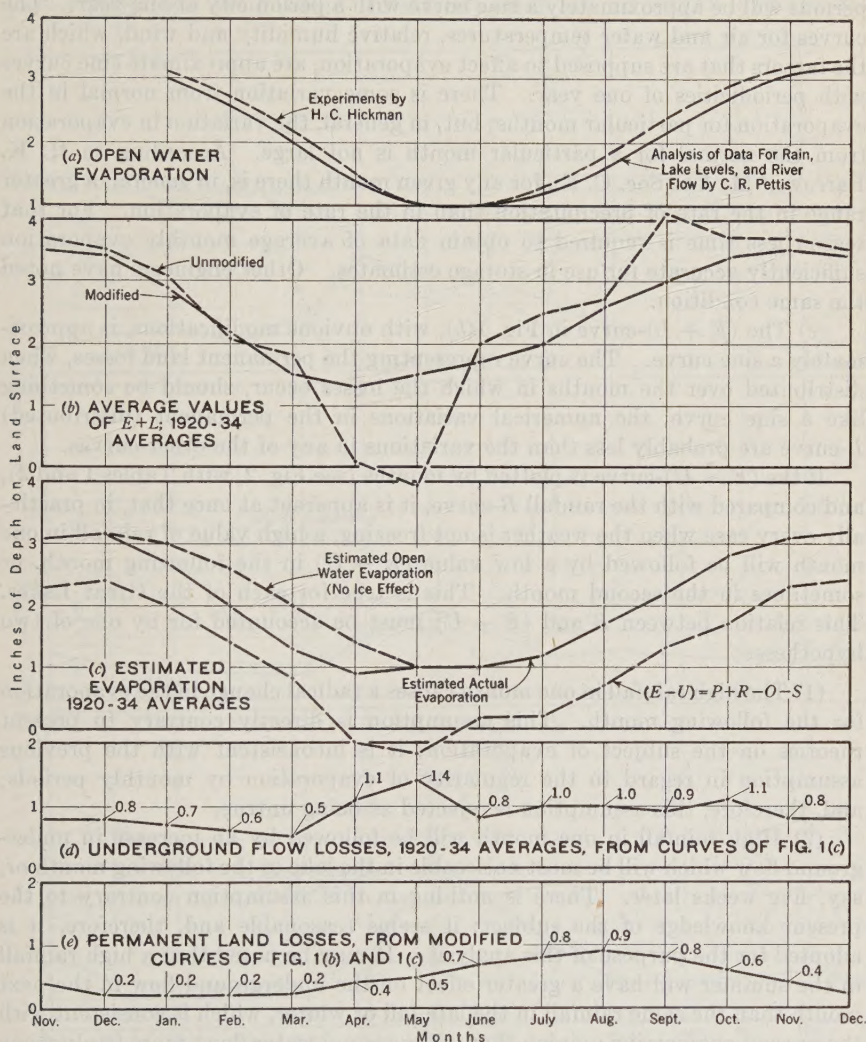


FIG. 1.—HYDROLOGICAL DATA APPLYING TO LAKE SUPERIOR

rated by the analysis of curves in this study. The flow of underground water even in the winter has been indicated by Mr. Horton who states:² "In case of sandy soils with low field moisture capacity, infiltration takes place at a relatively high rate even when the ground is frozen." Messrs. H. K. Burton

² National Research Council Report, 1936, p. 351.

and J. Cecil Alter state:³ "The mountain snow-layer melts continually from the bottom, the moisture leaching steadily into the soil."

(b) It is assumed that the normal open-water evaporation curve for monthly periods will be approximately a sine curve with a periodicity of one year. The curves for air and water temperatures, relative humidity and wind, which are the factors that are supposed to affect evaporation, are approximate sine curves with periodicities of one year. There is some variation from normal in the evaporation for particular months; but, in general, the variation in evaporation from the normal for a particular month is not large. According to H. K. Barrows,⁴ *M. Am. Soc. C. E.*, for any given month there is, in general, a greater range in the rate of precipitation than in the rate of evaporation. For that reason less time is required to obtain data of average monthly evaporation sufficiently accurate for use in storage estimates. Other engineers have noted the same condition.

(c) The $(E + L)$ -curve in Fig. 1(b), with obvious modifications, is approximately a sine curve. The curve representing the permanent land losses, when distributed over the months in which the losses occur, should be something like a sine curve; the numerical variations in the permanent (distributed) L -curve are probably less than the variations in any of the other curves.

If the $(E - U)$ -curve is plotted by months (see Fig. 2, with Tables 1 and 2), and compared with the rainfall B -curve, it is apparent at once that, in practically every case when the weather is not freezing, a high value of rainfall in one month will be followed by a low value $(E - U)$ in the following month, or sometimes in the second month. This is true for each of the Great Lakes. This relation between B and $(E - U)$ must be accounted for by one of two hypotheses:

(1) The high rainfall in one month causes a radical change in the evaporation for the following month. This assumption is directly contrary to present theories on the subject of evaporation; it is inconsistent with the previous assumption in regard to the regularity of evaporation by monthly periods; and, therefore, this assumption is rejected as being untrue.

(2) High rainfall in one month will be followed by an increase in underground flow which will be most noticeable in the lake in the following month or, say, five weeks later. There is nothing in this assumption contrary to the present knowledge of the subject; it seems reasonable and, therefore, it is adopted for the purpose of this analysis. It may be noted that a high rainfall in the summer will have a greater effect on the underground flow in the next month than the same rainfall in the late fall or winter, which is consistent with the present engineering opinion that underground water flows more freely when the temperatures are warm than when the temperatures are cold (see Table 1).

There is a considerable flow, R , from the surface streams through the winter; November, 0.9 in.; December, 0.7 in.; January, 0.6 in.; and February, 0.5 in. Since the ground in the Superior basin is ordinarily covered with snow during these months, it is assumed that most of this winter flow comes from under-

³ National Research Council Report, 1936, p. 534.

⁴ "Water Power Engineering," by H. K. Barrows, p. 83.

ground sources. The surface streams can tap only the portion of the underground water that is above certain levels; the underground water below these levels can reach the lake only through underground channels.

The winter underground flow is deduced by the following analysis: The 6-yr period 1920-1925 was a period of relatively small annual rainfall (average 26.6

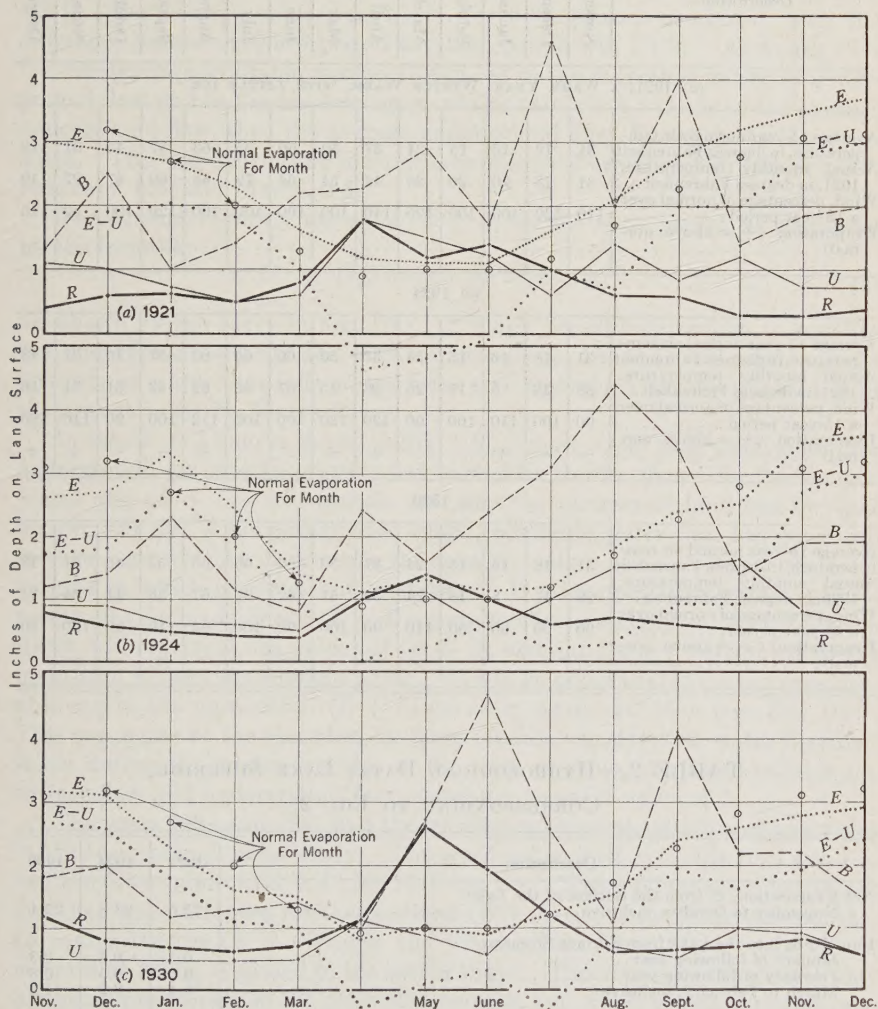


FIG. 2.—ESTIMATED EVAPORATION AND UNDERGROUND FLOW; LAKE SUPERIOR

in.); and, the 6-yr period 1926-1931 had a greater annual rainfall (average 29.8 in.). The average annual temperature for the two periods varied by less than 0.5° F. If the winter evaporation, December to March, for the two periods is assumed to average the same, the values of $(E - U)$ indicate that the underground flow from December to March for the second period was greater than that for the first period by 0.9 in.

TABLE 1.—TEMPERATURE AND WIND RECORDS; LAKE SUPERIOR;
CORRESPONDING TO FIG. 2.

Description	November	December	January	February	March	April	May	June	July	August	September	October	November	December
(a) 1921; A WARM YEAR; WINTER WARM, WITH LITTLE ICE														
Average 15-year normal air temperature, in degrees Fahrenheit	31	18	13	15	24	37	50	60	65	63	57	45	31	18
Actual monthly temperature, 1921, in degrees Fahrenheit	31	23	20	20	26	42	51	64	72	64	60	47	27	19
Wind, percentage of normal over a 15-year period	110	120	100	100	120	140	100	100	100	100	120	100	82	110
Evaporation (+ = above normal)	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(b) 1924														
Average 15-year normal air temperature, in degrees Fahrenheit	31	18	13	15	24	37	50	60	65	63	57	45	31	18
Actual monthly temperature, 1924, in degrees Fahrenheit	36	28	5	17	26	36	45	57	62	62	53	51	31	10
Wind, percentage of normal over a 15-year period	90	100	110	100	90	120	120	100	100	112	100	90	110	120
Evaporation (+ = above normal)	-	-	+	...	...	+	+	...	...	+	+	-	+	+
(c) 1930														
Average 15-year normal air temperature, in degrees Fahrenheit	31	18	13	15	24	37	50	60	65	63	57	45	31	18
Actual monthly temperature, 1930, in degrees Fahrenheit	28	17	8	18	24	39	51	62	65	67	56	44	34	21
Wind, percentage of normal over a 15-year period	90	90	90	90	110	90	100	90	100	90	110	90	100	80
Evaporation (+ = above normal)	...	...	...	-	+	-	...	-	...	-	+	-	-	-

TABLE 2.—HYDROLOGICAL DATA; LAKE SUPERIOR,
CORRESPONDING TO FIG. 2.

Description	1921	1924	1930
Net Evaporation, <i>E</i> , from the Surface of the Lake:			
November to October, inclusive	25.6	23.8	22.1
Run-off, <i>R</i> , into the Lake from Surface Streams:			
January of following year	0.5	0.5	0.3
February of following year	0.5	0.5	0.3
March to February, inclusive	9.4	8.2	11.3
Net Underground Flow, <i>U</i> , into the Lake:			
January of following year	0.7	0.6	0.5
February of following year	0.6	0.6	0.5
March to February, inclusive	11.8	11.4	9.2
Rainfall, <i>B</i> , on Tributary Land Surface:			
November to October, inclusive	27.3	25.5	26.1
$R + U$: March to February, inclusive	21.2	19.6	20.5
$L = B - (R + U)$: From two items above	6.1	5.9	5.6

The rainfall in August, September, and October is a major (but not the sole) factor affecting winter underground flow. From Equation (2), the rainfall available for underground flow is $(B - R - L)$. Taking an average value of L for the given months from Fig. 1(d), and using known data, $(B - R - L)$ August to October, for the first period, was 3.4 in., and for the second period, 4.8 in.; the average value was 4.1 in. for both periods combined; and, the difference between the low period and high period was 1.4 in. Assuming that the difference in available rainfall (1.4 in.) is to the difference in winter underground flow (0.9 in.) as the average available rainfall (4.1 in.) is to the average underground flow, then the average underground flow, December to March, is 2.6 in. This was distributed to months as follows: December, 0.8; January, 0.7; February, 0.6; and March, 0.5.

The average monthly values of $(E + L)$ for the 15-yr period, as computed by the formula:

$$E + L = P + B - O - S \dots \dots \dots (3)$$

are shown by the curve in Fig. 1(b). For any period long enough to equalize the underground-storage and lake-storage effects, $(E + L)$ will represent the quantity of water that falls on the total area and which has not passed out of the area through St. Marys River.

In the $(E + L)$ -curve shown in Fig. 1(b), if more water than usual goes into underground (or snow) storage in any particular month, then L for that month—and also $(E + L)$ —will contain not only the permanent land loss for that month, but also a temporary loss, which represents water that has gone into storage, and which will decrease the formula values of $(E + L)$ for the later months in which it comes out of storage. It is evident that certain adjustments may be made in the $(E + L)$ -curve to obtain a modified $(E + L)$ -curve which will represent the values of $(E + L)$ with land losses distributed to the months in which they actually occur. It will be noted that there is a considerable sag in the unmodified $(E + L)$ -curve in April and May (see Fig. 1(b)). This sag is due to the fact that, in these months, considerable water that had fallen during the winter months, in the form of snow, becomes available for surface flow and underground flow, causing a negative value of L .

The years 1924 and 1931 had the smallest winter precipitation of any years in the 15-yr period under study. The April value of $(E + L)$ for 1924 was 1.1, and the May value of $(E + L)$ for 1931 was 1.4. These values are only slightly less than those adopted for the modified $(E + L)$ -curve for these two months. In comparing the $(E + L)$ -curve and the modified $(E + L)$ -curve, it will be noted that 3.0 in. is gained in the spring thaw. This represents the water that has gone into storage in the preceding months, and which comes out of storage at the time of the thaw. The difference between the $(E + L)$ -curve and the modified $(E + L)$ -curve (Fig. 1(b)) is caused by the varying effects of storage on the values of L .

If the modified $(E + L)$ -curve is compared with a sine curve, it will be noted that there is a slight sag in the winter months, ending about May. This is caused by a certain area of ice forming near the shores of the lake in the winter, which reduces the evaporation. Lake Superior very seldom, if ever, freezes

over entirely. It is doubtful if as much as half of the lake has frozen over during the period 1920-1934.

Before an attempt is made to analyze the curves for individual years, it is desirable to ascertain the approximate shape of the E -curve for an average year. The average monthly values of $(E - U)$ for the 15-yr period are plotted in Fig. 1(c). Since it is assumed that U is positive at all times, all points of the E -curve must lie above the corresponding points of the $(E - U)$ -curve; in each case it is by an amount that is equal to the underground flow for the particular month. Previously, herein, average values of U were assumed for December to March. This assumption yields points on the E -curve for December to March, with the maximum point of the E -curve in December. For open-water evaporation, the minimum point of the curve can be assumed to occur about six months from the maximum point, or about June. The evaporation experiments, reported in this Symposium by Mr. Hickman, indicate that the minimum monthly evaporation to be expected on Lake Superior will not be less than 1 in. (land area unit). It will be assumed that the minimum evaporation in May and June is 1.0 in. per month. The open-water evaporation curve can now be obtained by drawing an approximate sine curve between the high points and the low points, and through the other points determined. The actual evaporation curve, or the full-line curve in Fig. 1(c), is obtained for the month of April by considering that a reduction in evaporation, due to ice, continues through this month.

From the E -curve (Fig. 1(c)), the $(E - U)$ -curve (Fig. 1(c)), and the modified $(E + L)$ -curve (Fig. 1(b)), the average monthly values for U and the permanent distributed values of L can be obtained. The curves for U and L are shown in Fig. 1(d).

The U -curve is higher in the warm months, and lower in the winter. The highest point is in the spring thaw, when the melting snow is added to the rainfall. The curve reflects the higher rainfalls in July and September, by increased flow in August and October.

The L -curve (Fig. 1(d)) may be considered to be caused primarily by land evaporation and transpiration. The shape of the L -curve suggests that the land-evaporation curve is somewhat similar to that of the ordinary pan-evaporation experiment, being higher in the summer, and, that transpiration losses vary with the activity of vegetable growth. Attention is called to the fact that "land evaporation," as the term is used in this paper, means the evaporation proper (water vapor leaving the land surface), minus condensation (water vapor absorbed from air by soil). According to some investigators, the rate of condensation is considerable.

An estimate has been made of the monthly evaporation for each one of the fifteen years in the period 1920-1934; the result of this detailed analysis for three typical years is shown in Fig. 2, with Tables 1 and 2. The methods used in the analysis have been evolved as the result of an extended study.

The average air temperature and relative wind velocities were computed for each month from data supplied by the U. S. Weather Bureau (see Table 1); a decided departure of either one of these factors from normal for any month will generally have a noticeable effect on the evaporation for that month.

Relative humidity was computed for each month; an effort was made to relate the monthly values of relative humidity to the corresponding data for evaporation, but the conclusion was reached that the monthly relative humidity is more the result of the evaporation than it is the cause of evaporation. For this reason, relative humidity was not used in the analysis; which is equivalent to making the assumption that, for the 15-yr period, the values of relative humidity remain normal according to the period of the year considered.

In the analysis, the first step is to plot monthly values of the $(E - U)$ -curve; then values of E are assumed for each month, which best comply with the following conditions:

(1) If air temperature is normal for the month, and has not been abnormal for the months immediately preceding, and if the wind is normal for the month, E should be nearly normal for the month, as shown by the E -curve in Fig. 1(c).

(2) A sudden lowering of the temperature for one month will tend to cause a higher value of E for this month; this accords with Dalton's law, since water temperature tends to follow the air temperature, but with a considerable lag.

(3) If air temperatures are above normal for a few months (say, three or more), water temperature will probably be above normal, and E will be increased.

(4) In a cold winter, E will tend to decrease, due primarily to a larger area of ice formed on the lake.

(5) A relatively high wind will cause a higher value of E .

(6) The normal winter values of U previously deduced are assumed to apply, except where modification may be indicated by some of the other factors.

(7) The values of E in the spring months should be such as to reflect the spring thaw in the values of U ; and, for different years, the values of U in the spring thaw should have some relation to the winter precipitation.

(8) There should be a relation between the precipitation and the values of U . Abnormally high or low values of B , except in the winter, should be followed in general by high or low values of U within a month or two.

(9) In some cases, the conditions will be conflicting; a few minor discrepancies are to be expected, due to slight errors in the data, or to the method of treating relative humidity.

The application of the foregoing principles to three typical years is shown in Fig. 2, with Tables 1 and 2. The climatic data for each month are plotted on the vertical line beneath the given month. In Table 1, the first line of each sub-table is the average (15-yr) air temperature for the corresponding month. The second line gives the average air temperatures for the months in question. The effect of the air temperature is judged by a comparison of the first two lines. The third line gives the wind velocity for each month as compared with the average (15-yr) wind velocity for that month. The fourth line shows by $(E +)$ or $(E -)$ certain months in which the temperature and wind indicate that the evaporation for the particular months will be appreciably above or below normal for those months.

The $(E - U)$ -curve is computed by a transposition of Equation (1). The R -curve is drawn from the tabulated values obtained from the Geological

Survey data. The small circles in the figures indicate the normal evaporation for respective months, as previously determined. The E -curve indicates the estimated monthly evaporation, giving consideration to climatic factors, and to the conditions previously enumerated. The value of U for each month, as shown by the U -curve, is determined by taking the distance between the E -curve and the $(E - U)$ -curve.

For convenience in making comparisons, the B -curve, for rainfall on the land, is plotted on the same sheet.

Values of E , R , U , $(R + U)$, B , and L , are presented in Table 2, L being computed from a transposition of Equation (2), using different periods for the several factors, in order to reduce the error in land losses, L , due to temporary storage effect. The twelve-month period, November to October, inclusive, was used for B in this formula; and, March to February was used for R and U , for the following reasons: The precipitation (in the form of snow), from November to February, has a much greater effect on R and U in the spring thaw after March than it does on the winter flow of R and U . The winter flow is affected principally by the rainfall in October and the preceding months, so that the rainfall during the period used in the formula for B reaches the lake principally in the period used in the formula for R and U ; and the values of L computed by this method are fairly uniform for most years, since the storage effect will be small unless conditions are somewhat abnormal. The correlation between climatic factors and evaporation, and between rainfall and underground flow can be observed in Fig. 2.

The year 1921 was an unusually warm year, and the evaporation was high (25.6 in.). The high evaporation for this year is further substantiated by a correspondingly high value of $(E + L)$, which can be computed from known factors by Equation (3). The winter of 1930 apparently had more ice than either 1921 or 1924. It was the only year of the three with a November-to-March temperature below normal. The year 1921 had the highest winter precipitation, from November to March, and it also had the largest underground flow in the spring thaw in April and May. The curves in Fig. 2 indicate that there is a fairly close correlation between rainfall, B , and the total flow to the lake, $(R + U)$. The distribution of B between R and U , evidently, depends on other factors than those that have been shown.

Next, consider the possibility of errors in the data, and the effect that such errors might have on the values of E , L , and U . For the purposes of this analysis, it is believed that the values of O and S may be accepted as correct, and that minor errors are more probable in the values of P , B , and R . The following statements are believed to represent the principal effects of possible errors:

From Equation (1), $(R + U) = O + S + E - P$. If the values on the right are assumed to be correct, an error in R will cause an equal error in the opposite direction in U ; and to a considerable extent, errors in R will be compensated by opposite errors in U , without affecting the values of E and L .

From Equation (1), $E = P + (R + U) - O - S$. If O and S are assumed correct, and errors in R are compensated in the determined values of U , an error in P will cause an equal error in the same direction in E .

From Equation (2), $L = B - (R + U)$. If errors in R are compensated in the determined values of U , an error in B will cause an equal error in the same direction in L .

The collection of water in rain gages is subject to wind effects, and the water in most gages is subject to some slight evaporation. It is believed that both B and P may be slightly greater than the Weather Bureau data used, and that the values of E and L may be slightly larger than the determined amounts.

SUMMARY AND ACKNOWLEDGMENT

The results of this analysis for Lake Superior are as follows:

Land area	Inches of depth on land area
Normal annual rainfall on land is.....	28.2
of which land losses are.....	5.9
The remainder.....	<u>22.3</u>
Reaches the lake as:	
Surface run-off.....	11.6
Underground flow.....	10.7

Lake area	Inches of depth on lake area
Normal annual rainfall on lake is.....	28.2
Annual surface run-off to lake is.....	17.9
Annual underground flow to lake is.....	<u>16.5</u>
Total addition to lake in one year is.....	62.6
Of which annual evaporation is.....	35.6
And outflow from St. Marys River is.....	27.0

The writer has received assistance from a number of sources, especially from Messrs. Sherman Moore, H. C. Hickman, Jun. Am. Soc. C. E., L. D. Kirshner, and F. W. Townsend, of the Lake Survey, and Professors C. O. Wisler and W. C. Hoad, Members, Am. Soc. C. E., and E. F. Brater, Jun. Am. Soc. C. E., of the University of Michigan, at Ann Arbor, Mich. The data form a part of a thesis⁵ by the writer, entitled "Hydrology of the Great Lakes," presented to the University of Michigan in 1938, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

⁵ A copy of the thesis, including all observations and other data, has been placed on file in the Engineering Societies' Library, 33 West 39th Street, New York, N. Y.

EVAPORATION EXPERIMENTS

BY HAROLD C. HICKMAN,⁶ JUN. AM. SOC. C. E.

SYNOPSIS

The evaporation experiments reported in this paper were conducted at Duluth, Kewaunee, Detroit, and Buffalo, for the purpose of providing a basis for estimating the evaporation from the water surfaces of the Great Lakes. In order to be applicable to local conditions, an effort was made to keep the temperature of the water in the pans approximately the same as the temperature of the water in the open lakes. Data were secured which cover a greater variety of combinations of air and water temperatures and wind velocities at the evaporation pans, than any known heretofore. In applying these data to the Great Lakes it was assumed that the evaporation from the open lakes, for a given air temperature, water temperature, and wind velocity, would be the same as the observed evaporation from the experimental pans for the same combination of air temperature, water temperature, and wind velocity.

The readings were analyzed and plotted on two charts, from which an estimate of the monthly (or daily) evaporation from the Great Lakes can be made. In these charts it has been assumed that the relative humidity and barometric pressure correspond to the average conditions that existed on the shores of the lakes, at all four stations, during the particular time of the year in which the data were being obtained. The experiments indicate that the effect of the wind on evaporation is fundamentally different from that indicated by the common evaporation formula. The rate of evaporation from open-water surfaces when the air temperature is below freezing has been investigated for the first time.

INTRODUCTION

The physical conditions that affect evaporation on the Great Lakes are quite different from conditions in comparatively shallow lakes. Because of the great depths involved (Lake Superior being as much as 1 300 ft deep in parts, Lake Michigan 920 ft, Lake Huron 750 ft, Lake Erie 210 ft, and Lake Ontario 760 ft), the water temperatures tend to remain relatively constant. Measurements of water temperatures in Lake Superior indicate that the entire body, below a depth of 180 ft, remains at a temperature of approximately 39.4° F throughout the year, which is the temperature of maximum density. In summer, the upper water is at a higher temperature than the lower body of water; and, in general, the temperature becomes increasingly warmer from a depth of 180 ft to the surface. In winter, the upper water is colder than the lower body;

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and, in general, the temperature becomes increasingly colder from the lower depths to the surface.

The average wind velocity on the lakes is about 10 miles per hr, which is the 15 yr average for four stations located around Lake Superior, the stations being about 100 ft above the lake surface where the wind velocity is comparable to that on the lake. There is considerable evidence to indicate that the effect of the wind is to cause a circulation and interchange of water between the upper and lower layers of the lake, and that there is some interchange most of the time. The effect of this interchange is to keep the surface temperature, which affects evaporation, cooler in spring and summer than would be the case in a shallow body of water; and, the water temperature lags considerably behind the air temperature in the spring and summer when the air temperature is rising. There is a similar lag in the water temperature in the fall and early winter when the air temperature is decreasing. As far as is known, none of the lakes freezes entirely over in the winter, although such a condition might be possible for a short time.

John R. Freeman, Past-President and Hon. M. Am. Soc. C. E., and others who have studied the subject have made attempts to deduce the lake evaporation from the standard evaporation formulas. Realizing that his results were not satisfactory, Mr. Freeman stated⁷ that, "Evaporation is at least a matter of great scientific interest, and a precise knowledge of the causes leading to change in its amount could be of use * * *. The collection of accurate statistics can not be begun too soon." After considerable study, he recommended the following procedure for the collection of data:

(1) A few months of experimental work, with relatively inexpensive equipment, for obtaining accurate values of constants in the formulas, by means of which evaporation can be estimated from standard records of the U. S. Weather Bureau Stations, which give the temperature, dew point, and velocity movement of the air.

(2) At each lake, one, or preferably two, evaporation tanks, on opposite sides (one in Canada and one in the United States) each preferably 6 ft or 8 ft in diameter by 4 ft to 5 ft in depth, of rigid shape, set on a rigid support high enough above the lakes to escape waves, and located on some projecting pier or on the shore. This type of tank should have provision for warming the water in winter barely enough to keep the ice from freezing on the surface, should have a device for agitating the surface slightly, and an anemometer should be set beside it.

(3) One daily temperature measurement shown by the maximum-minimum thermometers should be made along with observations for all the meteorological factors affecting the evaporation.

(4) Comparison should be made between the wind velocities at the pan and those recorded at the regular Weather Bureau Station in the same vicinity.

Because present formulas were not satisfactory for the required determination, new experiments which were more or less in accord with Mr. Freeman's recommendations were undertaken.

⁷ "Regulation of the Great Lakes," by J. R. Freeman, p. 421.

DESCRIPTION OF EQUIPMENT

All stations were located near the lake shore away from any buildings or land obstructions which might create atmospheric disturbances. The design and arrangement of the equipment approximated that used by the Weather Bureau as nearly as possible in order to facilitate comparison of data. The dimensions of the pan and relative positions of the instruments were identical. However, the pan had several new features which heretofore had never been used.

Design of Pan.—In order to control and regulate the temperature of the water in the pan, heat had to be supplied in winter and refrigeration in summer. The original design, shown in Fig. 3, called for a water-jacket around the pan

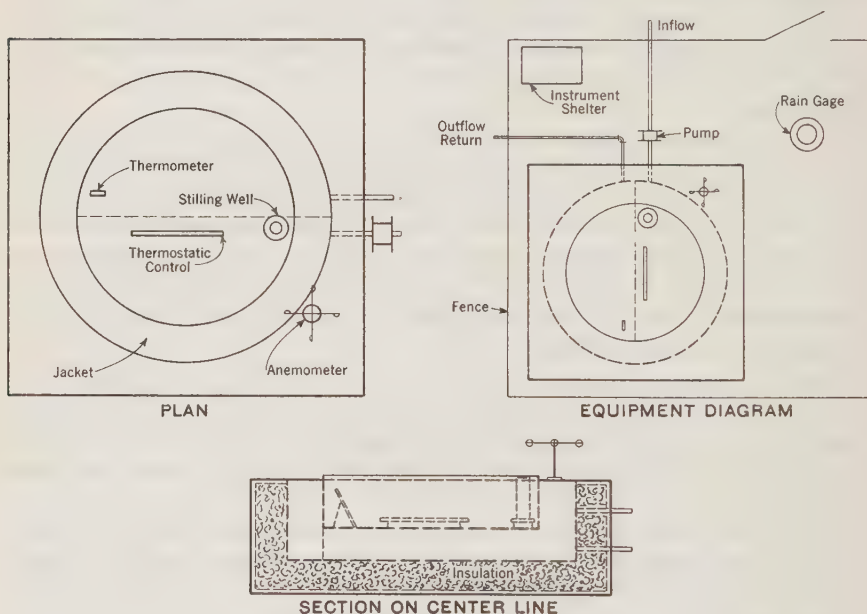


FIG. 3.—DESIGN OF DETROIT EVAPORATION UNIT

where warm or cool water could be circulated. This design was modified in two cases because of local conditions. At Duluth, enclosed electrical heating elements were submerged in the pan water; and at Detroit, electrical heating elements were placed in the de-watered jacket. The supply of heat was regulated by thermostatic control. All units were cooled in summer by circulating cold water around the tank. The supply of cooling water was regulated periodically, by hand, as the need arose. The source of supply was either cold well-water or water pumped from the lake at a depth of 20 ft or more. The pans were placed in large insulated boxes which aided in the regulation of the temperature.

It has been mentioned that an attempt was made to keep the temperature of the pan water as nearly as possible to mid-lake temperatures at all times.

Due to mechanical difficulties, the control was far from perfect; but the results were entirely satisfactory when analyzed by the method which was used and which does not require that the pan water be at the same temperature as the lake water.

Average Daily Temperature.—A maximum-minimum thermometer was placed in the pan water to obtain the mean daily temperature. It was assumed that for all practical purposes the mean of the maximum and the minimum water temperature for the 24-hr period represented the average temperature for the period. As a check on this assumption, observations every half hour for 24 consecutive hours were made on a number of different days. The thermometer was also read for each of these different days. The average of the 48 half-hour readings for each day, in all cases, checked the mean of the maximum-minimum value for the same day within 0.5 degree.

The method of obtaining the average daily air temperature was the same as that used by the U. S. Weather Bureau. The mean of the maximum and minimum thermometers gives the average temperatures, accurately for the day, except in rare instances.

Other Equipment.—The total daily movement of wind over the pan was measured by a standard anemometer placed at the edge of the pan and several inches above the water surface. These daily values were reduced to miles per hour before being used in the analysis. Rain and snow gages were placed around the pan to record precipitation. Wet-bulb and dry-bulb thermometers were supplied to all observers for daily observations of relative humidity and only one reading a day was taken in the immediate vicinity of the station.

RESULTS OF EXPERIMENTS

Because of the similarity of the equipment and the method of obtaining the daily readings, it can be assumed that mechanical inconsistencies and personal errors were reduced to a minimum. For purposes of analysis, all daily observations were grouped according to water temperatures, air temperatures, and wind velocities, regardless of location, it being assumed that the relative humidity and barometric pressure were normal for the particular temperature combination under consideration. For certain temperature combinations, this may not be true; but if a sufficient number of observations are taken within any one range, the average relative humidity value for that range will approach normal. The accuracy of a statistical analysis of this nature depends on the number of observations.

Master Chart.—The daily readings, listed according to temperatures and wind velocities, were arranged again into groups with a water and air temperature range of 5 degrees. For purposes of illustration, one group is described briefly: 44 daily readings—11 from the Duluth station, 14 from Kewaunee, 10 from Detroit, and 9 from the Buffalo station—where the average daily air temperature of each reading was between 40° and 45° and where the average daily water temperature was between 45° and 50°, were included in this group. The centroid of these 44 readings was found and plotted, and the average of these readings was assigned this point. The average wind velocity of the group of readings was found to be 5 miles per hr. Approximately 300 daily readings

from the four stations were grouped, averaged, and plotted in this manner. An additional 300 observations daily, scattered throughout the period of the experiments, were not used. These 300 readings represented days during which there was considerable rain or snow accompanied by high winds. Under these conditions, the evaporation pan did not collect the same amount of precipitation as the rain gage, and although individual readings of the evaporation pan "catch" were sometimes high and at other times low, it was decided not to include these irregular observations in the averages because of these discrepancies.

Some groups had as many as eighty individual readings and others had only five. The average wind velocities in the various groups or squares ranged from 4 to 6 miles per hr, with most of the squares averaging 5 miles per hr. Each individual square was studied in order to determine the effect of the wind on evaporation in that square. It was found that the increase in the amount, due to an increase in the wind velocity, did not vary in the same proportion throughout the range of the experiments. The proportion in each square was different and followed a well-defined plan. The value of average evaporation, in those squares where the average wind velocity was either greater or less than 5 miles per hr, were decreased or increased, according to the proportion for the respective square, to correspond to a value of evaporation based on a 5-mile wind.

Contours representing equal lines of evaporation were drawn. Fig. 4(a) is the final result of this work representing inches of evaporation per month instead of inches of evaporation per day. Daily values may be obtained by dividing by 30. The curves are based on a wind velocity, measured at one foot above the water surface, of 5 miles per hr. It has been assumed that relative humidity and barometric pressure correspond to the average conditions that existed during the particular period of the year in which the data were being obtained at the four stations. In order to determine whether discrepancies, due to location or methods, existed in the data, charts for each station were made. No irregularities in the slope or position of the contour lines were evident. Fig. 4(b) represents values of monthly evaporation with a wind velocity of 10 miles per hr, and Fig. 4(c) represents values of monthly evaporation with zero wind velocity according to the formula⁸ proposed by Adolph F. Meyer, M. Am. Soc. C. E.

$$E = 30 (V - v)(0.5 + 0.05 W) \dots \dots \dots (4)$$

Temperature Loop.—The range of the two master charts (Figs. 4(a) and 4(b)) is sufficient to cover average conditions on the Great Lakes, and monthly values of evaporation may be obtained directly from them if the respective mean monthly air and water temperature and wind velocity data are available. It is known that the air temperature for individual days drops down well below the low point of the charts. Should it be necessary to obtain values for extreme ranges in temperature or wind velocities, the curves may be extended; daily observations under extreme conditions have been plotted, and they checked the extended contours very well.

To obtain the monthly values of open-water evaporation for any lake, it is necessary to have accurate information as to the air temperatures over the lake,

⁸ "Elements of Hydrology," by A. F. Meyer, p. 238.

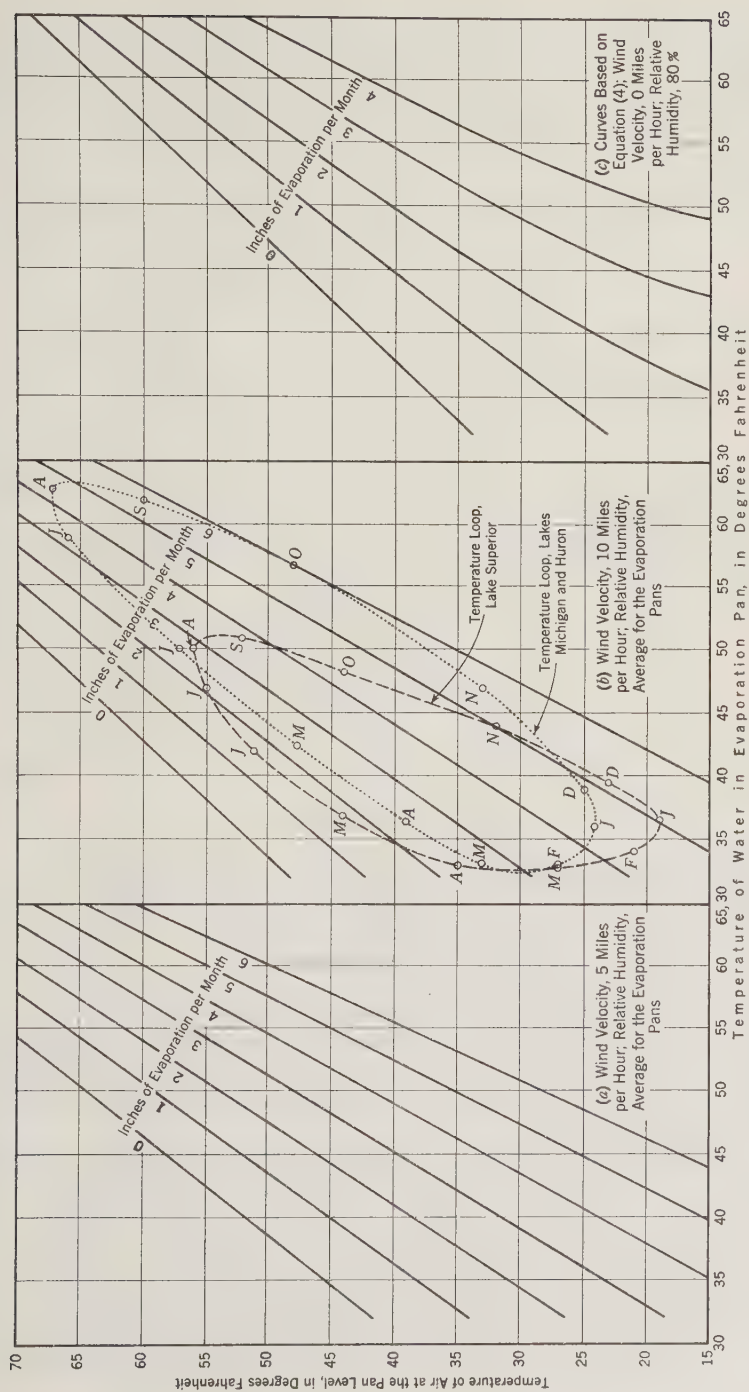


FIG. 4.—MONTHLY EVAPORATION CHARTS

the average water temperatures, and the average wind velocity over the lake. Considerable attention was given to these factors. Mean monthly air temperatures obtained from the records of the U. S. Weather Bureau Stations along the shore of the lakes do not represent mid-lake conditions. Readings observed out on the lake differ materially from those taken on shore because the air is influenced by the temperature of the water, both in summer and in winter.

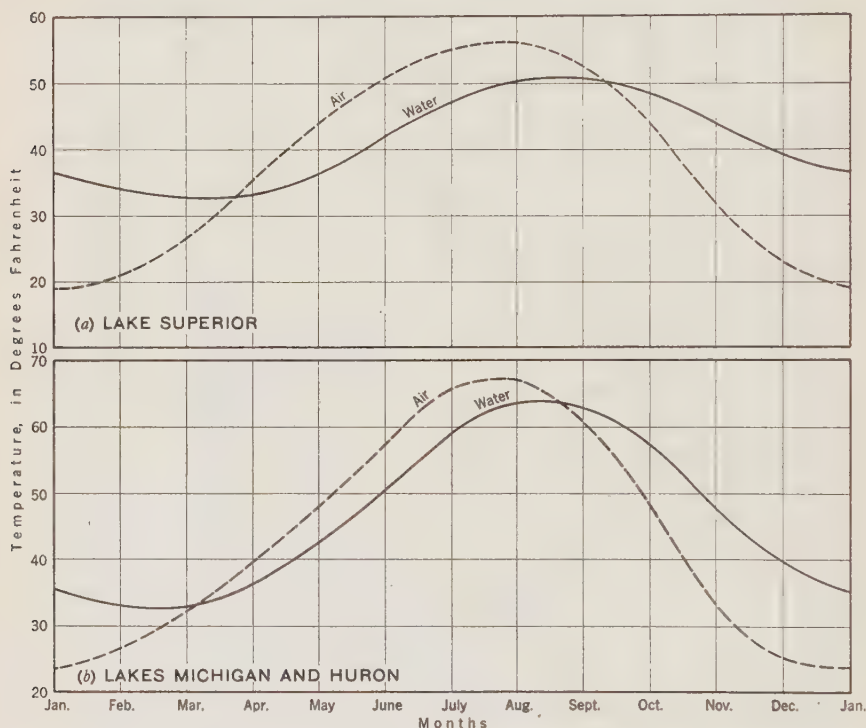


FIG. 5.—AVERAGE MEAN MONTHLY VALUES OF AIR AND WATER TEMPERATURES, WITH OPEN-WATER CONDITIONS

The mean monthly air temperatures as shown in Fig. 5 represent average values deduced from readings observed at the middle of the lake. Information pertaining to temperatures, both water and air, was obtained from the records of Lake Survey steamers, lake freighters, ferry boats, lighthouses, and municipal water-supply departments.

Seasonal air temperature variations in the lake region are considerable, and although these variations are somewhat decreased by the lakes, they do affect the temperature of the water. Large bodies of water, and particularly Lake Superior, react slowly to climatic variations in temperature. In fact, the yearly range of the average mean water temperature as shown in Fig. 5(a) is only 18 degrees. Due to the size and depth of the lakes, it can readily be seen that a large amount of heat is necessary to produce temperature changes in the water. The lake is never at the same temperature throughout, at any one time,

and the temperature in the middle may be 20° lower than that recorded near the shore. No matter how the air temperature varies, and at what rate, the temperature of the surface water lags behind that of the air. The mean monthly values for lakes Superior, Michigan, and Huron, shown in Fig. 5, represent average open-water conditions.

The surface water is subject to frequent changes in temperature when there is no wind; but since this condition seldom exists, interchange of surface and sub-surface water is occurring continually. The wind is one of the most important factors to be considered in the study of lake evaporation for this reason.

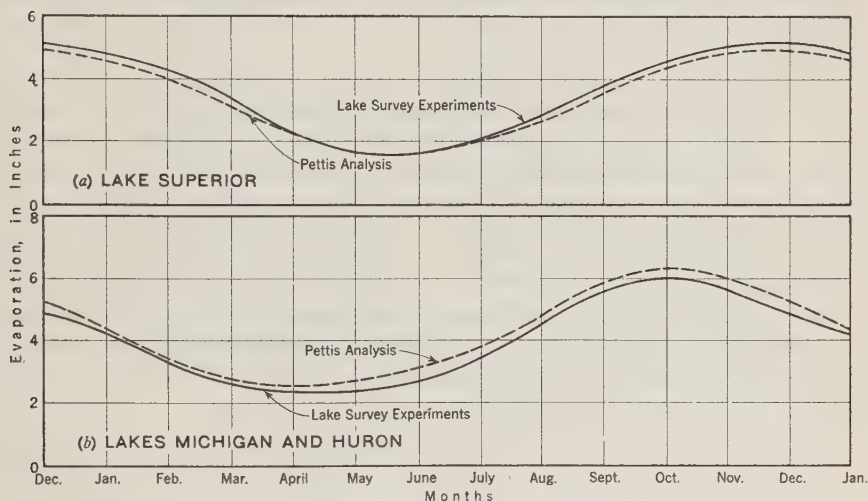


FIG. 6.—EVAPORATION FROM THE LAKE SURFACE

In strong winds, spray is thrown into the air, thus increasing the evaporation. Observations at Weather Bureau Stations on land indicate an average wind velocity of 10 miles per hr and it is believed that the velocity over the water is at least as great.

If the normal mean monthly air and water temperatures for Lake Superior, as shown in Fig. 5(a), are plotted in Fig. 4(b), the points will form the broken-line loop shown. These normal monthly values are plotted in Fig. 6(a) and are compared with the values of normal monthly evaporation obtained by an entirely different analysis made by Colonel Pettis. It was for this comparison that the study was made. A temperature loop and values of monthly evaporation for lakes Michigan and Huron are shown in Fig. 4(b) and by the dotted loop in Fig. 6(b).

FACTORS AFFECTING EVAPORATION

Evaporation from the lakes, as shown by the charts, has been related to air and water temperature and wind velocity. The evaporation, obtained as a result of the experiments, cannot be related directly to relative humidity or barometric pressure as measured at standard Weather Bureau Stations. The

temperature of the air and water influencing evaporation, and likewise the velocity of the wind, may be used with considerable accuracy, but no correlation could be found between evaporation and relative humidity. No evidence could be found that the amount of evaporation varied with either the relative humidity as read at the station or as determined at neighboring Weather Bureau Stations. Although both relative humidity and barometric pressure have not been related directly to evaporation, they have been considered. It is logical to assume that if a sufficient number of observations are made in the same locality, over a sufficiently long period of time, using a particular air-and-water temperature combination, the resulting average relative humidity and barometric pressure will be characteristic for that temperature combination, for that locality.

In other words, evaporation for any month, say September, as obtained from Fig. 4(b), is the most probable value of the evaporation for that month, under normal or average conditions of relative humidity for that particular month. This is true since the evaporation curves for this particular locality were obtained from numerous daily readings of evaporation, taken under conditions of relative humidity which existed in this region, in this particular season. Fig. 4(b) thus gives the results in the most desirable form to use in any study, either general or specific, which involves average or probable conditions.

In order to emphasize the reason for basing this analysis on the three factors, air and water temperature and wind velocities, it might be well to analyze the ordinary evaporation formula that has been in use for some time.⁹ Considering the equation as a modification of Dalton's Law

$$E = K (V - v) \left(1 + \frac{w}{c}\right) \dots \dots \dots (5)$$

in which K = constant for particular conditions; w = mean velocity of wind in miles per hour; and c = coefficient expressing the effect of wind. It will be noticed that the measure of evaporation is the difference between V and v , multiplied by a constant and a wind correction. In other words, the measure of evaporation expressed by Equation (5) depends upon the saturation deficit of the atmosphere. If the saturation deficit is small, the evaporation is small. Should a condition exist in which the water temperature on Lake Superior was 40° and the air 42.4°, with a wind velocity of 10 miles an hr and a relative humidity of 80%, as measured by the Weather Bureau, a condition quite common for this lake, the evaporation for the day would be zero, according to Equation (5). The same temperature and wind combination on the master chart (Fig. 4(b)) would give 0.09 in. of evaporation for the day.

In order to use Equation (5), the temperature of the water and air must be known. After reducing the air temperature to the dew-point temperature, dependent on the relative humidity, each is converted into pressures. It is assumed that the moisture in the air influences the rate of evaporation. This cannot be denied, but experiments indicate that under the influence of wind, evaporation occurs consistently, although Equation (5), used with the proper climatic factor, indicates that the evaporation would be zero. Evaporation

⁹"Regulation of the Great Lakes," by J. R. Freeman, 1926 Edition, p. 135.

increases relative humidity, and it is believed that relative humidity, as indicated by the experiments, is a result of evaporation more than a cause of evaporation.

Experiments conducted in different parts of the United States by the U. S. Weather Bureau show evidence that a humidity gradient exists, varying inversely as the elevation above the earth's surface. Even if the relative humidity is 100% at the water surface, there is atmosphere directly above where the

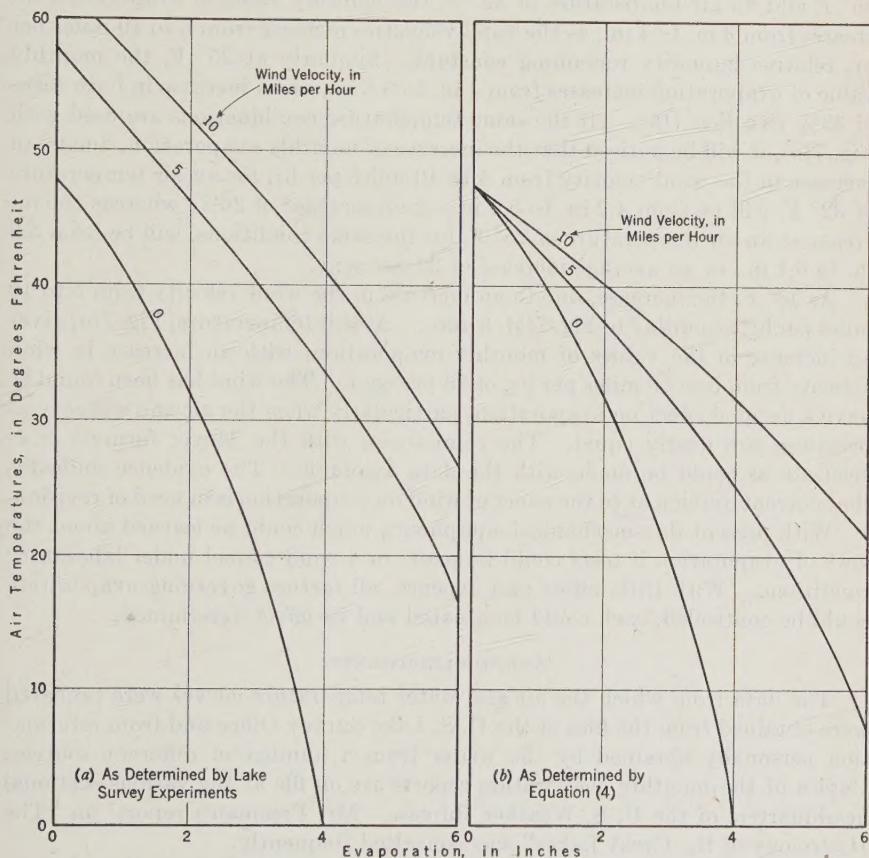


FIG. 7.—VALUES OF MONTHLY EVAPORATION FOR A CONSTANT WATER TEMPERATURE OF 45 DEGREES FAHRENHEIT

percentage is less, and there is a continual escape of vapor upwards. It seems logical to assume, for the purposes of this presentation, that evaporation is dependent on temperatures and wind velocities, and that relative humidity on the Great Lakes tends to follow the seasonal averages.

If the wind factor in Equation (5) is considered, it will be noticed at once that E approaches zero as the difference between the vapor tension and the vapor pressure becomes less. When the values of V and v are equal, evaporation ceases, regardless of the wind velocity. Experiments described in this paper

show that this is not true. The air temperature is higher for zero evaporation, assuming a constant water temperature, as the wind velocity is increased (see Fig. 7), and similarly the water temperature is lower for zero evaporation, assuming a constant air temperature, as the wind velocity is increased. According to Mr. Meyer,⁸ an increase in the wind velocity from zero miles per hr to 10 miles per hr, assuming that other factors in Equation (4) remain constant, doubles the evaporation. With a constant water temperature of 45° F and an air temperature of 32° F, the monthly value of evaporation increases from 3 in. to 4 in., as the wind velocities increase from 5 to 10 miles per hr, relative humidity remaining constant. Similarly at 25° F, the monthly value of evaporation increases from 4 in. to 5.3 in., or an increase in both cases of 33% (see Fig. 7(b)). If the same temperature combinations are used with Fig. 7(a), it will be noticed that the increase of monthly evaporation, due to an increase in the wind velocity from 5 to 10 miles per hr, for an air temperature of 32° F, will be from 4.2 in. to 5.3 in., or an increase of 26%, whereas the increase at an air temperature of 25° F, for the same conditions, will be from 5.0 in. to 6.1 in., or an average increase of 22 per cent.

At 48° F, the increase, due to an increase in the wind velocity from 5 to 10 miles per hr, according to Fig. 7(b), is zero. At this temperature, Fig. 7(a) gives an increase in the values of monthly evaporation, with an increase in wind velocity from 5 to 10 miles per hr, of 80 per cent. The wind has been found to have a decided effect on evaporation, particularly when the air and water temperatures are nearly equal. The comparison with the Meyer formula is as accurate as could be made with the data available. The evidence indicates that current opinion as to the effect of wind on evaporation is in need of revision.

With present-day mechanical equipment, much could be learned about the laws of evaporation if tests could be made in a wind tunnel under laboratory conditions. With little effort and expense, all factors governing evaporation could be controlled, each could be isolated and its effect determined.

ACKNOWLEDGMENTS

The data from which the air and water temperature curves were prepared were obtained from the files of the U. S. Lake Survey Office and from information personally obtained by the writer from a number of different sources. Copies of the monthly evaporation reports are on file at the various sectional headquarters of the U. S. Weather Bureau. Mr. Freeman's report⁷ on "The Hydrology of the Great Lakes" was consulted frequently.

The data form a part of a thesis¹⁰ by the writer, entitled "Evaporation from the Great Lakes," presented to Lawrence Institute of Technology, Highland Park, Mich., in 1938, in partial fulfillment of the requirements for the degree of Doctor of Engineering. The writer wishes to acknowledge the invaluable assistance of Colonel Pettis and Mr. Sherman Moore, of the Lake Survey, Professors H. L. Woolfenden and G. P. Brewington of Lawrence Institute of Technology; Professor C. W. Chamberlin of Michigan State College, at East Lansing, Mich.; and valuable constructive criticism of Professors C. O. Wisler and W. C. Hoad of the University of Michigan, at Ann Arbor.

¹⁰ A copy of the thesis, containing all observational data, has been filed for reference in the Engineering Societies Library, 33 W. 39th Street, New York, N. Y.

